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SCIF e^- Guns, Ion Input and Controlled Operation†

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e–GUNS

The e–guns acquired for and used on the SCIF experiment have hot cathode electron emission sources. We have been told[1] that their current-voltage emission characteristics will follow the (usual) Richardson emmission scaling with voltage of

$$I_e = N_g k_g E^{3/2} \tag{1}$$

(N_g = number of guns used), and that they are supposed to put out I_e = 25.0 A current per gun, at E = 25.0 keV, nominal voltage. These design numbers yield an output scaling coefficient of $k_g \approx 6.32E\text{-}6$ for E in eV and I_e in A.

Now, as pointed out since early May, 1991[2] (in meetings held at SAN and in subsequent memos), the EKXL and GJ codes have shown clearly that the SCIF machine operated with an e–gun voltage of E = 22.5 ± 2.5 keV can reach a core density of ca. $n_c = 1E12/cm^3$ in the MR mode only if ion input is at the machine edge ($r \approx R$) along cusp lines, and if repellers of $\alpha_r = 0.9$ effectiveness are used.

However, as also shown previously (see Figures 1a, 1b), to go beyond this density along the $W = E/(B_oR)^2$ line set by the limiting E, B_o, R values of the SCIF design ($W \approx 3E\text{-}4$ keV/(kGcm)^2; E = 25 keV, B_o = 3.1 kG, R = 92 cm) requires vast increases in electron drive current, to a maximum of about $I_e \approx 18{,}000$ A, before reaching the "runaway" unstable portion of the G_j vs. Z parameter space that defines the system operating regime.

As we presented at the DARPA review meeting on July 30, 1991, and provided earlier in writing[3], a much easier path to high density and reactor-like behavior can be found by operation at HIGH W such that the beta = 1 ($\langle r_b \rangle$=1) line is reached at G_j near unity - i.e. as an almost non-magnetic electrostatic confinement machine. This would test the WB mode physics of interest, rather than the MR mode physics of no intrinsic interest to the Polywell™ concept.

EKXL code calculations and parallel phenomenological modelling analyses show that this sort of operation will require a current drive whose relationship to electron energy follows a different scaling law than that of the present SCIF e–guns. The $\langle r_b \rangle$=1 line is found to be reached in the WB mode by operation with a drive current related to voltage by the approximate formula $I_e = 10E^{1/2}$. The value of W that corresponds to $\langle r_b \rangle$=1 at G_j = 1 is about 20 keV/(kGcm)^2, thus $E = 2E\text{-}2(B_oR)^2$ gives the drive voltage allowed for a given (B_oR) product value, where units are E = eV, B_o = G, R = cm.

If the SCIF guns are driven hard enough, to higher voltage, their effective impedance Ω_g will drop; $\Omega_g = E/I = 1/k_gE^{1/2}$. It is then of interest to determine at what voltage the SCIF guns can match the requirements of the $\langle r_b \rangle$=1 line. To find this, set the two scaling laws for electron current equal to each other, as

$$I_e = N_g k_g E^{3/2} = 10E^{1/2} \quad (2)$$

which yields N_gE = 1.6E6 eV. If N_g = 6 (maximum number of square faces on SCIF) then E = 266.7 keV is required. This voltage level requires a total current of ca. I_e = 5200 A and a drive power of P ≈ 1.4E9 W; impossibly beyond the capabilities of the SAN equipment, facility, or of SDG&E.

What is needed is e-guns of low impedance. Reformulating the scaling in terms of gun impedance it is easy to show that the critical drive voltage for guns that behave as $E^{3/2}$ emitters will be given by

$$E_{crit} = 267\Omega_g \quad (3)$$

for six guns with E_{crit} in eV and Ω_g in ohms. If Ω_g = 1 ohm, then E = 267 V, etc. The power level of this last example is only about $P = N_g I_e E$ = 240 kW, within reach of a practical drive power supply. What is needed is low impedance guns; without these little progress can be made.

More detailed and exact calculations of these features and requirements for WB operation are given in the table shown in Figure 2, and in the graphs of Figures 3 and 4. These calculations are based on more exact formulations of the problem than that given above, as derived and discussed in a separate, more detailed study of WB mode operation.[4]

Ion Input

In addition, it is essential that the device be started with as low density background gas as possible, so that background gas will not continue to dominate the device behavior over the short pulse time allowed by the present e-gun drive power supply system.[5] Of course, as noted from the concept's origin[6,7], good control of ion input is also essential.

Ion input is favored at or near the edge, but along a cusp or funny vertex line, and it must be controlled within a factor of 3-4x or so, on well depth[8], to follow the rise in electron current once the well is established. Initial deflection of ions by the B field will be small at conditions of large W, when B is kept low, and when the ions are put in on cusp axes, and slightly inside the maximum field point. Even with higher fields, the transverse ion deflection can be kept within tractable limits, if diamagnetic effects do function, down to some reasonable values of W for experimental purposes.[9] This type of ion input and control can be used to obtain successful convergence of ion flow in the potential well established by the e-gun drives. The e-guns also must be driven controllably so that current can be reduced as ion current falls, without internal arcing or arbitrary shutoff, if the device operating conditions are to be achieved.

Controlled Operation

Finally, it should be noted that a proper experimental machine, able to test the basic features of the concept, should be able to be operated in a steady-state mode, as the concept has always been a steady-state device.

Indeed, the "adiabatic time-dependence" of the EKXL code simply calculates distributions et al for a steady, stable operating condition of the system. "Steady-state" here means over time periods very long compared to the electron AND ion lifetimes in the system.

In such a steady-state system, full control of ion and electron input is required, as above, so that adjustments can be made in real-time of these drive and balancing inputs. The present arrangement of equipment for the SCIF experiment does not permit this, and it can be achieved ONLY by the acquisition of new sources (and associated power supplies) of different character than those now pursued for electrons and ions. And this requires new money (as planned in the original program) for the proper equipment.

A general summary of the differences between the fusion system concept and the current SCIF experiment is given in Figure 5. The origins of the difficulties experienced in proving concept viability with SCIF, as currently constructed, are evident from the comparison given in this figure. Parenthetically, it must be noted that almost all of the differences are the result of choices made under extreme budget pressure due to the DARPA-directed cutback of funds made early in the program.

Pulsed operation using background ions or neutral gases can not be used as a practical means of starting the system, although some specially set up experiments may be able to circumvent the inherent flaws in this approach. IF the system were steady-state, then it COULD be started successfully from a neutral gas background state, for continued electron drive would eventually ionize and burn out the background, leaving only those ions that are able to be trapped in the well. From this point in time, the ion input could be started under anode height control, as described above, to run the system. With this mode of operation, the degree of initial background gas would not matter to eventual steady operation, and the extreme difficulties associated with the present pulsed experiment would not appear. But, again, such a test system must await the acquisition of additional new money to support the further theoretical analysis, modelling design, and device development for the full experimental program required.

REFERENCES

1. Verbally, in early-1991 private conversations with R.A. Jacobsen

2. EMC2 Monthly Reports for April/May/June 1991; EMC2-0491-01, EMC2-0591-01, and EMC2-0691-01

3. 4 June 1991 FAXes to N.A. Krall and R.A. Jacobsen in San Diego office, detailing scaling laws along the beta = 1 ($\langle r_b \rangle = 1$) line and their consequences for MR vs WB operation of SCIF

4. EMC2 Technical Report, EMC2-0891-02, "Electron Current and Beta Limit Line Operation in WB Mode," Robert W. Bussard and Katherine E. King

5. EMC2 Technical Report, EMC2-0691-03, "SCIF Startup With Neutral Gas Background," Robert W. Bussard

6. R.W. Bussard, G.P. Jellison, and G.E. McClellan, "Preliminary Research Studies of a New Method for Control of Charged Particle Interactions," Final Report to DNA Contract No. DNA001-87-C-0052, Pacific-Sierra Research Corp., 30 November 1988

7. U.S. Patent 4,826,646 on Polywell$_{tm}$ concept, issued May 2, 1989

8. Presentation of EKXL code calculational results for variable anode height in SCIF, showing well blowout, reported at Wiz III meeting, and in EMC2 Technical Report, EMC2-0691-02, "Computer Modelling of SCIF Experiment Performance," Robert W. Bussard and Katherine E. King

9. As described in EMC2 Technical Report, EMC2-0691-04, "Ion Deflection in Simple Power Law Potential Wells," Robert W. Bussard

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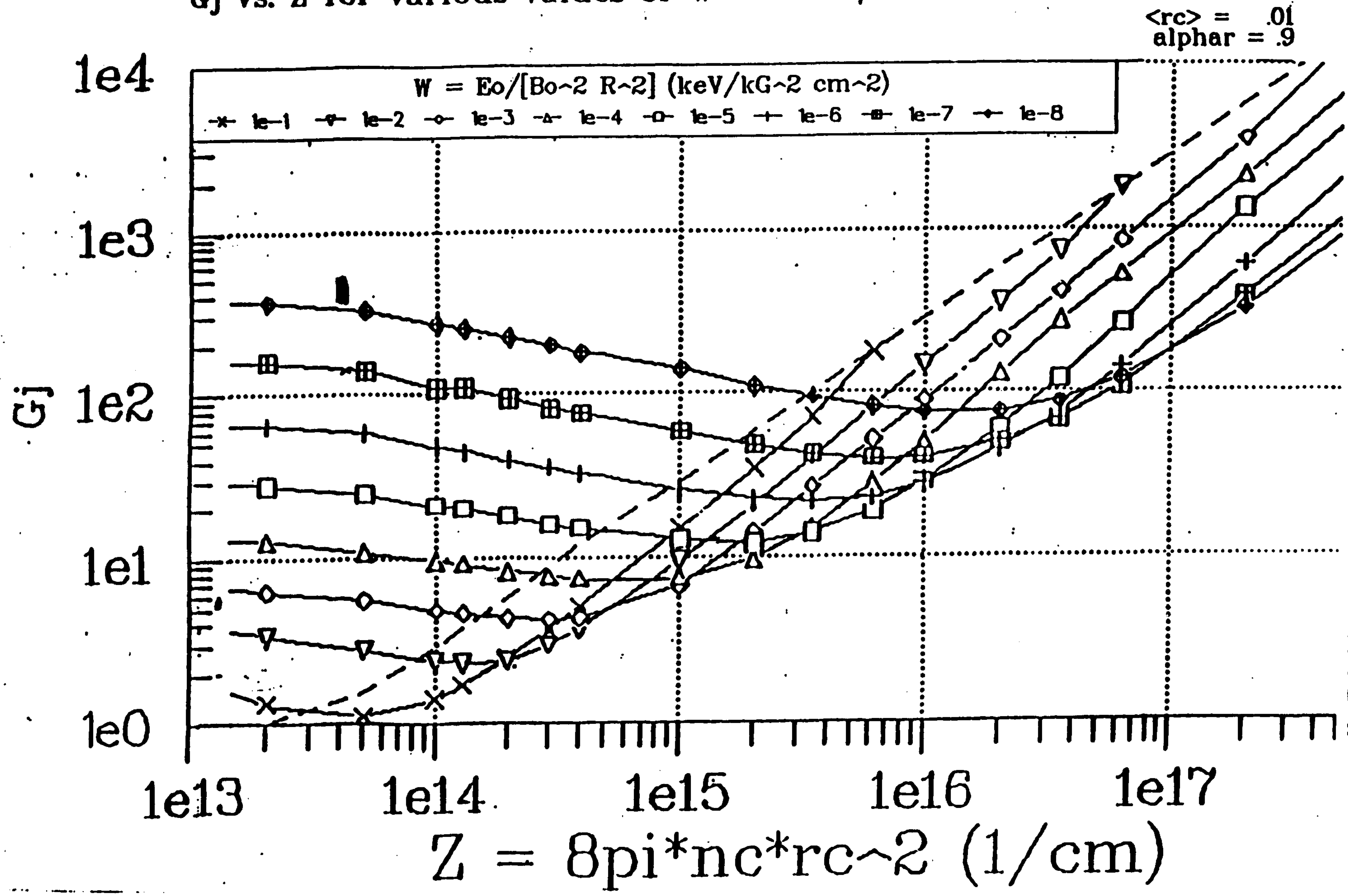
FIGURE 1A

Gj vs. Z for various values of W



Gj vs. Z for indicated Ie (kA)

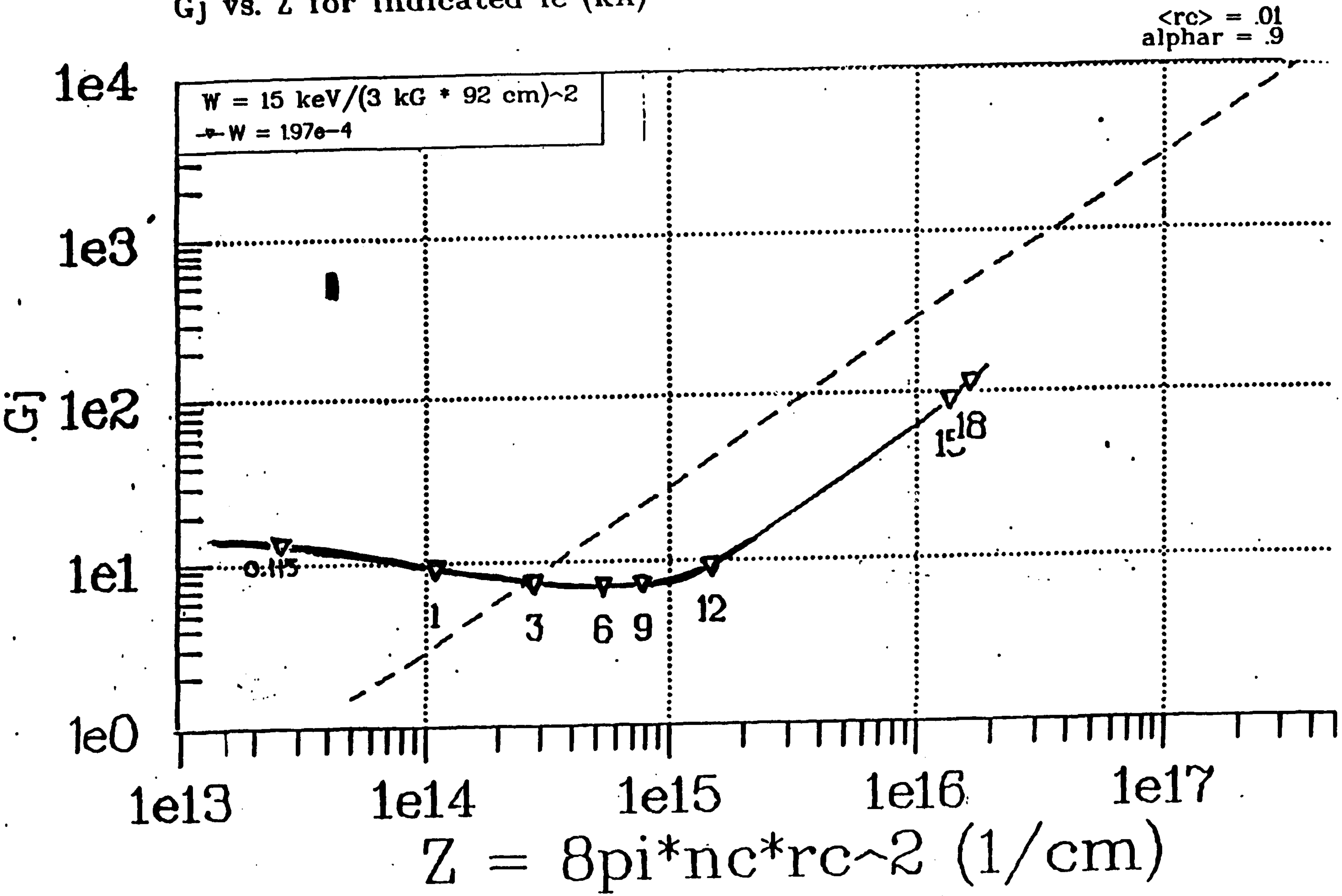


FIGURE 1B

SCIF Parameters Necessary to Test Wiffle Ball (WB) Physics 8/23/91

R (cm)	=	92				
Bmax (kG)	=	3				
<ro>	=	.01				
# e- guns	=	6				
Bmin (G)	=	1.00	3.00	5.00	10.00	15.00
Eo (keV)	=	.12	1.08	3.00	12.00	27.00
Ie (A)	=	96.95	290.86	484.77	969.55	1454.32
Pinj (W)	=	1.16365e4	3.14185e5	1.45456e6	1.16365e7	3.92731e7
Impedance	=	7.43	22.28	37.14	74.27	111.41
nc (1/cm3)	=	1.8648e19	2.0720e18	7.4592e17	1.8648e17	8.2880e16
nc (rb=1)	=	2.0720e12	2.0720e12	2.0720e12	2.0720e12	2.0720e12
Wlow	=	14.18	14.18	14.18	14.18	14.18
Whigh	=	1.5756e-6	1.418e-5	3.9389e-5	1.5756e-4	3.545e-4

FIGURE 2

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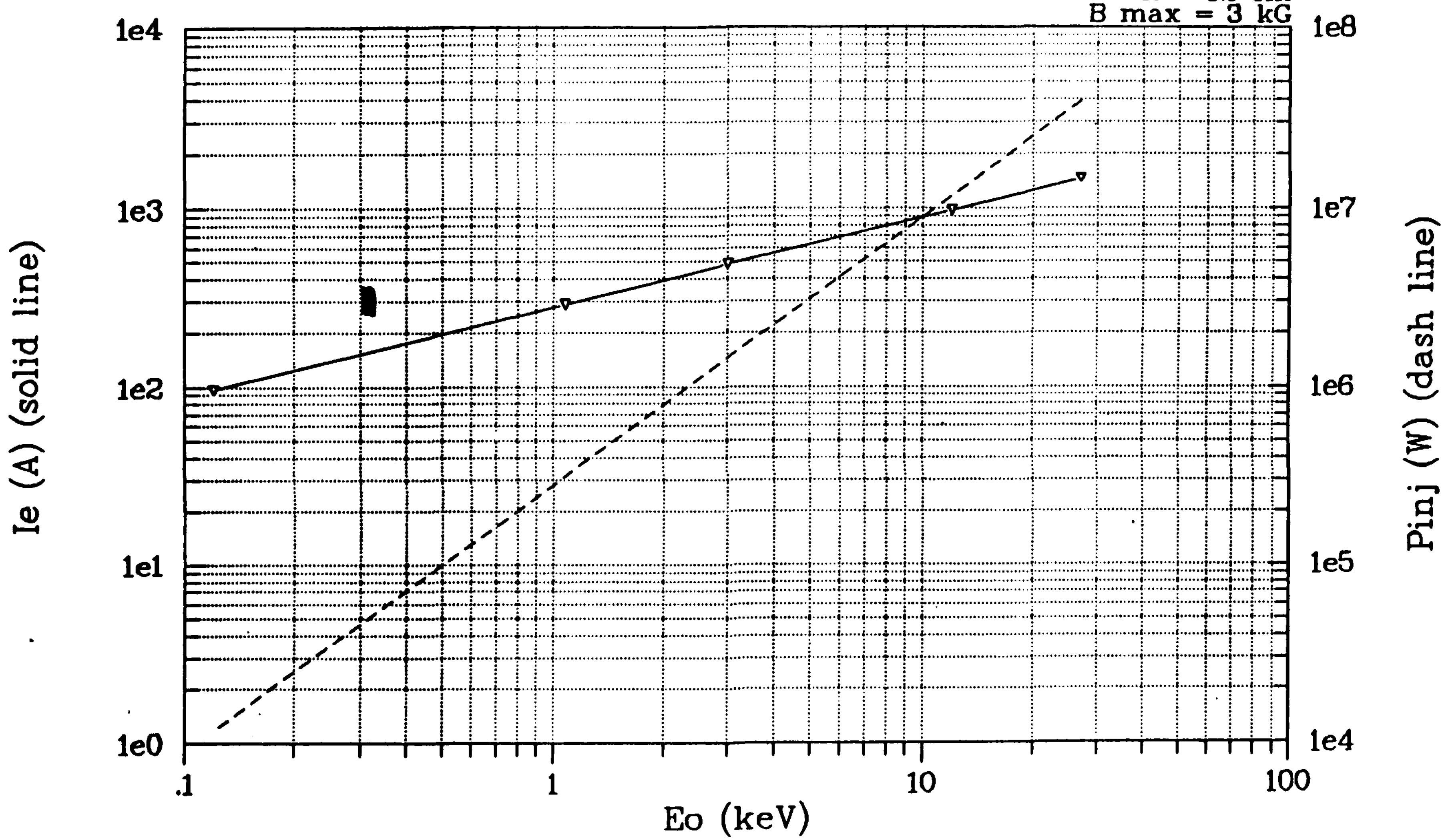
FIGURE 3

SCIF Parameters Necessary to Test Wiffle Ball (WB) Physics

R = 92 cm
B max = 3 kG



$\langle ro \rangle = 0.01$

W (low) = 14.18 [keV/(kGcm)~2]

8/23/1991

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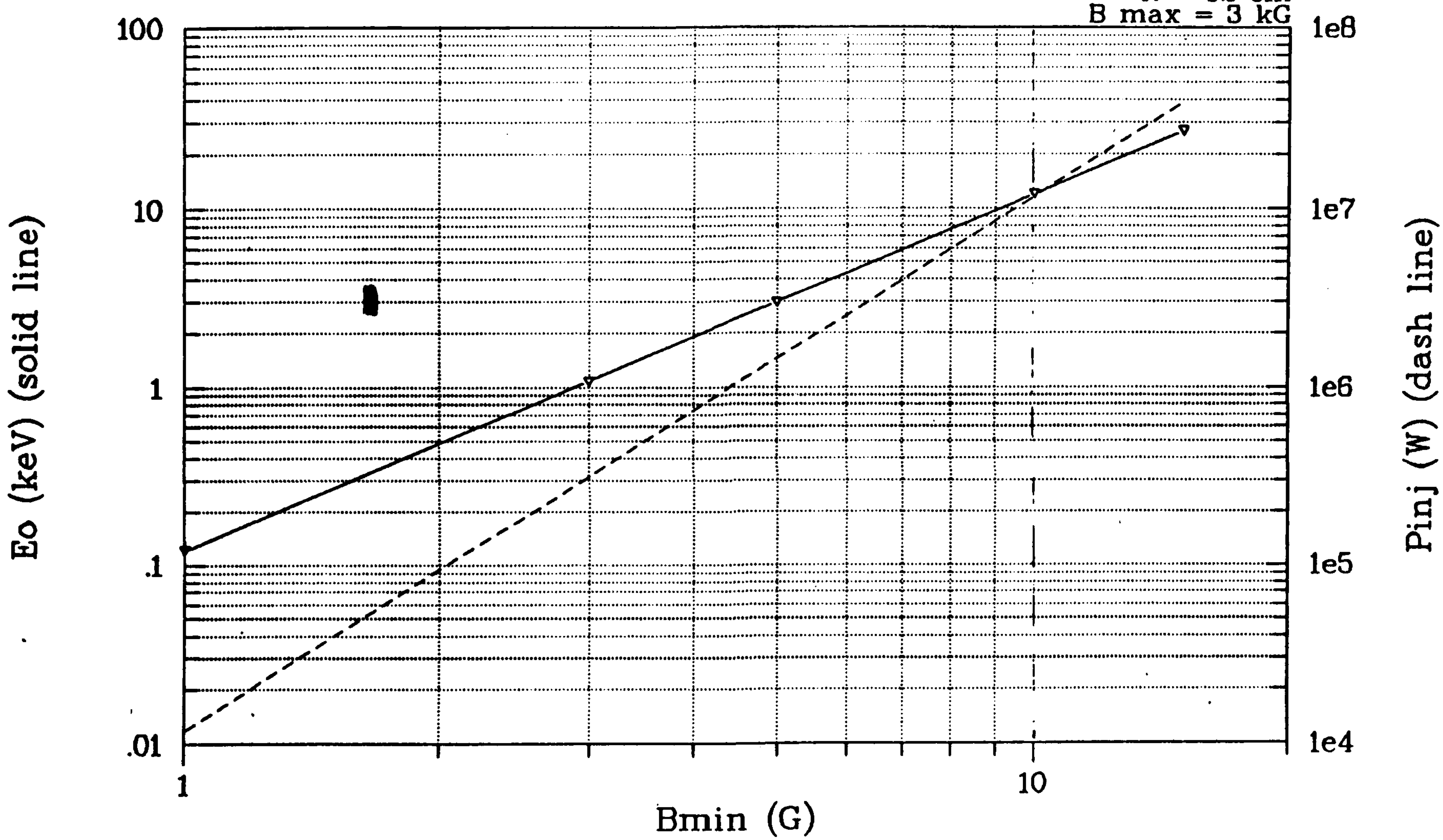
SCIF Parameters Necessary to Test Wiffle Ball (WB) Physics



<ro> = 0.01
W (low) = 14.18 [keV/(kGcm)~2]
8/23/1991

FIGURE 4

EMC2 FUSION SYSTEM CONCEPT	DTI GOVERNMENT EXPERIMENT
STEADY-STATE OPERATION	SHORT-PULSE OPERATION
NO BACKGROUND GAS NO IONIZATION INSIDE SYSTEM	DOMINATED BY INTERNAL BACKGROUND GAS IONIZATION
INDEPENDENT CONTROL OF ELECTRON VOLTAGE AND CURRENT INPUT	ELECTRON CURRENT DEPENDS ON VOLTAGE, NO CONTROL OF RISE RATES
CONTROLLABLE ION CURRENT ION EDGE CUSP INPUT	NO ION GUNS, UNCONTROLLABLE IONS THROUGHOUT SYSTEM
SIMULTANEOUS ELECTRON AND ION CURRENT CONTROL	ELECTRON INPUT NOT CONNECTED TO ION SOURCE

FIGURE 5

SCIF Parameters Necessary to Test Wiffle Ball (WB) Physics 8/30/91

R (cm) =	92				
Bmax (kG) =	3				
<ro> =	.1				
# e- guns =	6				
Bmin (G) =	1.00	3.00	5.00	10.00	15.00
Eo (keV) =	.12	1.08	3.00	12.00	27.00
Ie (A) =	193.91	581.73	969.55	1939.10	2908.64
Pinj (W) =	2.32729e4	6.28369e5	2.90912e6	2.32729e7	7.85461e7
Impedance =	3.71	11.14	18.57	37.14	55.71
nc (1/cm3) =	1.8648e17	2.0720e16	7.4592e15	1.8648e15	8.2880e14
nc (rb=1) =	2.0720e10	2.0720e10	2.0720e10	2.0720e10	2.0720e10
Wlow =	14.18	14.18	14.18	14.18	14.18
Whigh =	1.5756e-6	1.418e-5	3.9389e-5	1.5756e-4	3.545e-4

SCIF Parameters Necessary to Test Wiffle Ball (WB) Physics 8/30/91

R (cm)	=	92				
Bmax (kG)	=	3				
<ro>	=	.1				
# e- guns	=	6				
Bmin (G)	=	1.00	3.00	5.00	10.00	15.00
Eo (keV)	=	.12	1.08	3.00	12.00	27.00
Ie (A)	=	193.91	581.73	969.55	1939.10	2908.64
Pinj (W)	=	2.32729e4	6.28369e5	2.90912e6	2.32729e7	7.85461e7
Impedance	=	3.71	11.14	18.57	37.14	55.71
nc (1/cm3)	=	1.8648e17	2.0720e16	7.4592e15	1.8648e15	8.2880e14
nc (rb=1)	=	2.0720e10	2.0720e10	2.0720e10	2.0720e10	2.0720e10
Wlow	=	14.18	14.18	14.18	14.18	14.18
Whigh	=	1.5756e-6	1.418e-5	3.9389e-5	1.5756e-4	3.545e-4